Larhyss Journal, ISSN 1112-3680, n°45, Mars 2021, pp. 7-33

CARTOGRAPHY OF THE ZONES FAVOURABLE TO THE IMPLANTATION OF DRILLING CENTER OF THE CÔTE D'IVOIRE

CARTOGRAPHIE DES ZONES FAVORABLES A L'IMPLANTATION DE FORAGE CENTRE DE LA CÔTE D'IVOIRE

SAMAKÉ Y., ASSEMIAN A.E.*, SORO N.

Department of Geography, UFR CMS, University Alassane Ouattara (Bouaké, Côte d'Ivoire), Contact: +225 06 77 00 10, Address: 01 BP V 18 Bouaké 01

assmilea@gmail.com

Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received December 20, 2020, Received in revised form March 10, 2021, Accepted March 15, 2021

ABSTRACT

In the department of Tiébissou, most of the groundwater resources are contained in basement aquifers. In this region, 24% of the boreholes drilled are abandoned for reasons of drying up and negativity. The lack of knowledge of this aquifer is the main factor explaining this failure rate. This study aims to use remote sensing methods and GIS to locate the zones suitable for drilling to obtain good flow rates. Thus, the processing of the ASTER sensor DTM images allowed the extraction of the fracture network (1347 fractures) and the drainage network to determine the fracture and drainage density. Their integration in the drilling and climatic parameters, in multi-criteria analyses (GIS methods), allowed to determine the zones favorable to the implantation of drilling to obtain good flow rates. These are areas where groundwater is easily accessible, exploitable and capable of producing significant flows. These flows are scattered almost everywhere and especially a little more concentrated in the west. This will minimize the cost of drilling and will make it possible to supply drinking water to the large populations in these localities.

Keywords: Basement aquifer, groundwater, multi-criteria analysis, Remote sensing

RÉSUMÉ

Dans le département de Tiébissou, l'essentiel des ressources en eau souterraine est contenu dans les aquifères de socle. Dans cette région, 24% des forages réalisés sont abandonnés pour des raisons de tarissement et de négativité. La méconnaissance de cet aquifère est le principal facteur explicatif de ce taux d'échec. Cette étude vise à utiliser les méthodes de télédétection et les SIG pour localiser les zones propices à l'implantation des forages pour l'obtention de bons débits. Ainsi, le traitement des images MNT du capteur ASTER a permis d'extraire le réseau de fractures (1347 fractures) et le réseau de drainage, pour déterminer la densité de fracturation et la densité de drainage. Leurs intégrations dans les paramètres de forage et climatiques, dans des analyses multicritères (méthodes SIG), a permis de déterminer les zones favorables à l'implantation de forage pour l'obtention de bons débits. Ce sont des secteurs où l'eau souterraine est facilement accessible, exploitable et capable de produire des débits importants. Ceux-ci sont disséminés presque partout et surtout un peu plus concentrées à l'ouest. Ce qui minimisera le coût de foration et permettra d'approvisionner en eau potable des populations importantes dans ces localités.

Mots-clés : Aquifère de socle, eau souterraine, analyse multicritère, Télédétection

INTRODUCTION

Human life without safe drinking water is impossible. Groundwater in bedrock and continuous environments is a vital resource for meeting the freshwater needs of communities if it is protected from all forms of pollution (Fulvie and al, 2013). Basement rocks (crystalline or metamorphic) occupy important places both globally and in West Africa. Their groundwater resources, although modest, make a significant contribution to the economic development of the countries concerned, due to global warming and the frequent pollution of surface water. Knowledge on the fracturing of basement aquifers has recently made very significant progress. It has also been shown that it is the weathering processes that are at the origin of their aquifer potential. Indeed, basement aquifers now include, from top to bottom: unconsolidated alteration, characterized by relatively low permeability but significant water storage capacities, a stratiform fissured horizon, with tectonic fracture corridors (Lachassagne and Wyns, 2005; Dewandel and al, 2011). Open tectonic fractures are the most productive in groundwater and can contribute to several m^3/h, with instantaneous flows from nearby boreholes. (Roux, 2005; Lachassagne and Wyns, 2005). The interconnections between weathering, cracks and fracture corridors, as well as rainfall intensities, are factors that condition their aquifer potential. Currently, remote sensing allows the extraction of geological structures associated with geomorphological units indicative of faults, lithological contacts or ancient fractures, easily detectable by satellite sensors, thanks to their high sensitivity to surface roughness. MNT images from the ASTER satellite, for example, thanks to their spatial resolution of 30 m, make it possible to produce images that detect the morphology of the landscape, representing the morphostructural discontinuities that characterize the fracturing of the environment. In Côte d'Ivoire, with population growth and the effects of global warming, there is a real problem of drinking water supply in the base areas which occupy more than 97.5% of the territory. Surface waters are vulnerable to pollution of all kinds (agricultural, domestic) and their existence nowadays depends solely on the rainy seasons because of global warming. The department of Tiébissou located in the basement zone, subject of the present study, is in a situation of difficult access to groundwater. In fact, the Lakes Region, to which the department of Tiébissou belongs, benefited from state hydraulic allocations through the National Program of Human Hydraulics (PNHH) in 1993. This campaign made it possible to count 1176 water points (boreholes and then modern ones). However, of these 1176 structures, 538 were abandoned for various reasons (mechanical failure, drying up, water quality, etc.) and 128 were declared negative because they did not reach a minimum flow rate of 1 m^3/h to be declared positive, making a total of 766 abandoned structures, so 65%. This alarming failure rate can be attributed to the poor choice of drilling locations, chronic rainfall deficits in Côte d'Ivoire and lack of knowledge of the hydraulic and geometric properties of the aquifers (Soro and al. 2010). In addition, the coverage rate in the department of Tiébissou is being eroded by a failure rate estimated at 23% and a fairly recurrent drying up (Dje Bi, 2017). This study aims to show by remote sensing methods and GIS, the productive zones in underground water and very favorable for the implantation of boreholes with important flows, in order to allow a good coverage of the water needs in the department.

GEOLOGICAL AND HYDROGEOLOGICAL CONTEXT

The department of Tiebissou is located in the center of Côte d'Ivoire, between the longitude 4° 50'and 5°40' W and the latitude 6°50'30'' and 7°23'30'' N (figure 1).

It belongs to the region of Aries with an area of 2 410 km². The relief is essentially low plateaus with an average altitude of about 300 m. It is characterized by two very distinct types of geological landscape: the granitic landscape and the schist landscape (figure 2). The granitic landscape occurs mainly in the central part of the department. With an average altitude of 200 m, it is marked by gentler slopes. On the other hand, the schistous landscape is a more rugged relief with an altitude of up to 500 m. The aquifers of the department of Tiébissou are part of the aquifers of the volcano-sedimentary series. Indeed, they are very heterogeneous aquifers composed of schisto-quartz-sandstone complexes and green rocks folded and straightened by Eburnean tectonics (Aboubabaye, 2012). The aquifers in these series are characterized by a thicker alteration layer in places. As with any basement aquifer, one can distinguish alteration reservoirs, fractured horizon reservoirs and highly productive tectonic fracture corridors. Alteration thicknesses on these shales and granites are very developed in places. This basement is fed by an average annual rainfall of about 1200 mm. Vegetation is dominated by tree-covered savannah and pre-forest savannah with gallery forests. This vegetation develops on ferralitic and hydromorphic soils.

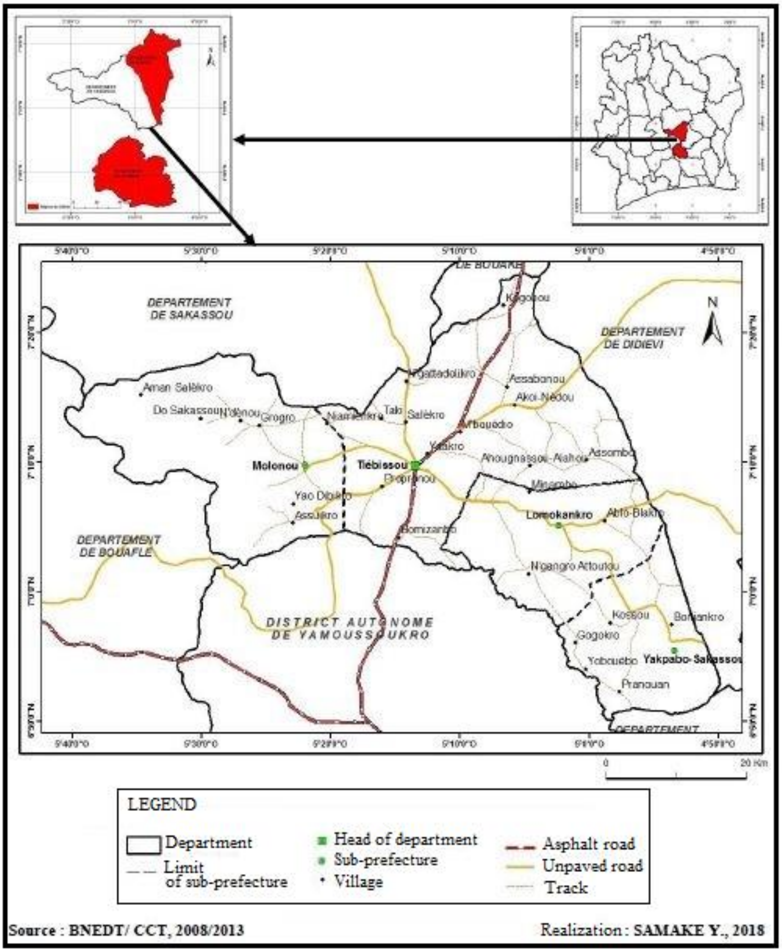


Figure 1: Geographical location of the study area

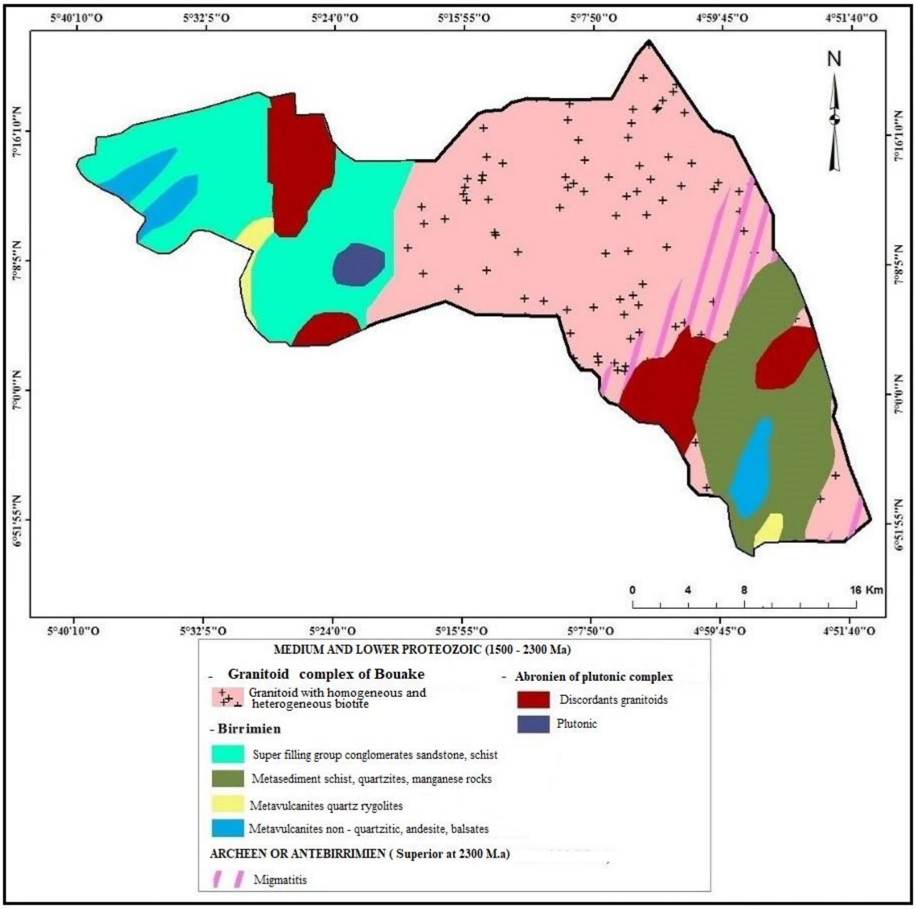


Figure 2: Geological map of the department of Tiébissou

MATERIALS AND METHODS

Data

The hydraulic data for this study were collected at the Yamoussoukro Territorial Hydraulic Directorate. They were taken from 324 borehole data sheets, 150 of which are well informed about the boreholes in operation. The information provided on this sheet are the parameters of the boreholes such as: the geological nature of the drilled environment, the operating flow rate (Q), the static level (NS), the total depth of the borehole (Pt), the thickness of the basement (ES), the thickness of alteration (EA), the depth of the first and second water inflow (AE1 and AE2), the measurements of the pumping tests and the geographical coordinates of each borehole. To map the geological structures (the fracture network) of this aquifer, we used a satellite image of the study area, downloaded from www.earthexplorer.usgs.gouv. This image is a DTM band from the ASTER sensor with 30 m spatial resolution. The references of this DTM band are shown in Table 1. The topographic (1/50000 scale), photo-geological (1/50000 scale) and geological (1/50000 scale) maps covering the study area were used for the validation of the structural lineaments. The climatic data are: rainfall, temperature, relative humidity, insolation...etc. These climate data were furnished by SODEXAM and cover the period 1960 to 2017. Several specialized softwares were used to process the various data, notably the ENVI4.7 software for processing the DTM band and the QBASIC program developed by Coulibaly (1997) for the calculation of fracture-induced permeability. This algorithm was developed at CURAT (Centre Universitaire de Recherche d'Application en Télédétection) of the Félix Houphouet Boigny university in Abidjan. The fracture and drainage densities and multi-criteria analyses required the use of ARG GIS 10.2 software. EXCEL and WORD software for statistics and text entry.

Table 1: References of the satellite image used in the study

Sensor	ASTER
Vector	TERRA
Date of acquisition	17/10/2011
Image	DTM (Digital Terrain Model)
Date of update	November 23rd 16
Size of the catch	1 arc second
Pixel size	30 m
projection	Géographique (wgs 84, zone30)

Source : www.earthexplorer.usgss.gouv (2018)

Methods

Extraction of the fracture network

Using ENVI 4.7 software, the fracture pattern was extracted from the DTM image of the ASTER sensor. This image, which highlights the morphology of the landscape, was subjected to a directional convolution filtering technique to enhance the morphostructural discontinuities characterizing the fracturing (Kabre, 2012), (figure3).

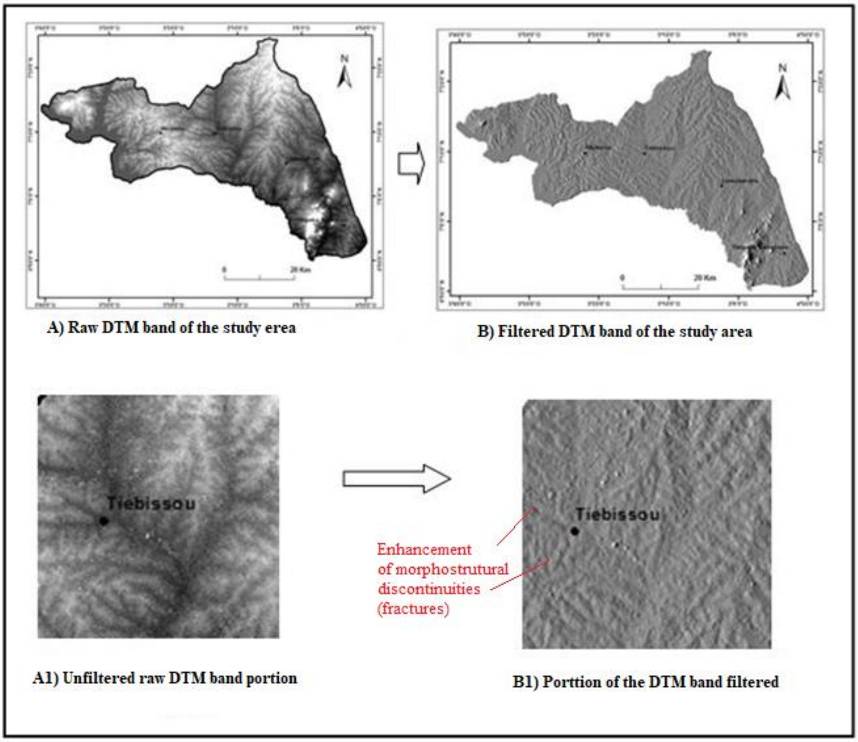


Figure 3: Directional convolution filtering on the DTM image of the study area, enhancing the fracture network

The extraction of fractures in linear forms was done manually by visual analysis on screen (Koussoube, 2010; Doubabaye 2012; Fulvie and al 2012; Assemian, 2014). The detailed lineament map obtained is validated with the help of the photo-geological maps covering the study area (Jourda and al, 2006; Youan Ta, 2008; Kabre, 2012). The fracture network thus obtained is exported to ARCGIS 10.2, to elaborate the fracture density map by interpolation. In addition, we have cross-referenced the drill hole exploitation rates to the fracture network to verify if the drill holes that are close to the fractures have significant exploitation rates. For this purpose, according to the Inter-African Committee for Hydraulic Studies (CIEH) (1978), these flows are classified as follows:

- Between 0 and 1 m^3/h, the flows are considered very low;
- Between 1 and 2.5 m^3/h, flows are low;
- From 2.5 to 5 m^3/h, the flows are qualified as high;
- Frm 5 to 10 m^3/h, the flows are qualified as high;
- Above 10 m^3/h, the flows are said to be very high.

GIS method for mapping favourable zones for the implementation of drilling at good flow rates

This work should consist of identifying areas where groundwater is easily accessible and exploitable, locating potentially water productive areas and areas suitable for drilling for high flow rates using GIS methods (Jourda and al, 2006; Youan Ta, 2008; Youan Ta and al, 2015 et Assemian and al, 2018). Here, the multi-criteria analysis method will be used (Jourda and al, 2006; Youan Ta, 2008; Assemian and al, 2014; Youan Ta and al, 2015; Assemian and al, 2018; Kouassi and al, 2012). According to Savané and Biemi, (2000), the criteria used to describe the Accessibility indicator are: probability of success and drilling depth. The probability of success is the percentage of positive drill hole flows (Q> 1 m^3/h) calculated in a given grid. Indeed, the study area was enamelled in 8 km squares for the calculation of the probability of success in these grids, due to the distribution of the drill holes. In addition, the operating flow rate criteria and static level are used to describe the exploitability indicator (Saley, 2003). According to Savané and Biemi, (2000), a water table is accessible when the depth to obtain a positive flow is low, similarly a zone is exploitable if the exploitation flow is significant for a low static level. Finally, according to Jourda and al, 2006, Assemian and al, (2014) and Youan Ta and al (2015), to define the Groundwater Potential indicator, the criteria used are: slope, effective infiltration, drainage density, fracture-induced permeability, weathering thickness and fracture density. The criterion of fracture-induced permeability (m/s) was developed from the treatment of the fracture map. Calculations of fracture-induced permeabilities according to the method of Franciss (1970) have been used by various authors including Savadogo (1984); Biemi (1992); Koussoubé (1996); Savané (1997); Jourda and al (2006); Koudou and al, (2011), Assemian and al, (2014). This method makes it possible to estimate the permeability of the subsoil with respect to the intensity of fracturing that has affected the basement. This approach, based on mathematical theories, facilitates the modeling of flow in a fissured environment. The application of the Franciss method requires the estimation of two parameters: C_i and K_{fi}. (C_i = ei/Li and K_{fi} = Ti / ei) in a given mesh or sector. Here ei: thickness of the crushed zone (m), corresponding to the difference between the depths of the last and first water inflows or the length of the strainer in the case where, the borehole has only one water inflow; Li: length of the fracture; Ci: empirical proportionality coefficient; K_{fi}: hydraulic conductivity of the sector (m/s) and Ti: transmissivity of the sector (m^2/s), calculated using the method of Cooper-Jacob (1946). The Cooper-Jacob method for the calculation of the transmissivity (Ti) over a borehole is defined as follows:

$$S = \frac{2{,}30.Q}{4\pi Ti}.\log\left(\frac{2{,}25.Ti.t}{u.d}\right)$$

with S: the drawdown (m) at time t during the pumping test; Q: the pumping rate (m^3/s); Ti: the transmissivity (m^2/s); d: the storage coefficient and t: the pumping time or duration (s) for a given drawdown S and u = r^2 (r: the radius of the borehole (m)). Thus, measurements (S_1; t_1), (S_2; t_2)....(Sn ;tn) allow to calculate the transmissivity Ti.

According to Franciss, the coefficient of permeability of a fracture is expressed by a second-order tensor and the tensor K, which expresses the cumulative effect of several fractures, is obtained by summing the tensors of each fracture contained in the space system under consideration. The moduli of the K vectors are the maximum (K_{max}) and minimum (K_{mini}) permeabilities along the major and minor axes of the ellipse and between them form an angle of 90° and are expressed according to the following formula:

$$\mathbf{K}\binom{max}{mini} = \frac{1}{2}(\mathbf{K}_{NN} + \mathbf{K}_{\infty}) \pm \sqrt{\frac{1}{2}(\mathbf{K}_{NN} - \mathbf{K}_{\infty})^2 + 4\mathbf{K}_{NO}^2}$$

Or K_{NN} and $K\infty$ are the permeabilities with respect to a North-South and East-West axis system. The mean induced permeability of the basement (Kmoy) is determined by the following relation:

$$Kmoy = \tfrac{1}{2}.\ (K_{max} + K_{mini}).$$

The application of this method requires a grid of the study area of 2410 km^2 in 98 circles of 5 km in diameter. Each georeferenced circle is inscribed within a 5 km square representing a mesh. Within each circle, the total number of fractures, the length of each fracture and their orientation are determined. After determining the values of the mean hydraulic conductivity (Kf = $3.5.10^{-5}$m/s) and the mean empirical proportionality coefficient (C = $5.4.10^{-3}$) of the region, the values of the induced permeabilities (K_{max} and K_{mini}) of each mesh are calculated. The application of the Franciss model makes it possible to integrate K_f and C and the geometrical parameters of the fractures to determine the values of the induced permeabilities of each circle. The QBASIC program developed by Coulibaly (1997) allows the calculation of the induced permeabilities of each circle of the base of the study area, integrating the Franciss method. The high values show that these zones are very productive in groundwater. Exploitation of the ASTER sensor DTM band under ARCGIS10.2 software, allowed not only the slope criterion map (%) to be established, but also the map of the hydrographic network and the variations in drainage densities in the study area. The exploitation of climate data allowed the estimation of the effective infiltration criterion in each 7 km grid cell of the study area by water balance approach (P= ETR + R + Ie) (Assemian and al, 2013; Assemian and al, 2018 and Koudou and al, 2018), based on the annual Turkish method. The annual Turkish method first determines the ETR according to the following equation:

$$\begin{cases} ETR = \dfrac{P}{\sqrt{0{,}9 + \left(\dfrac{P}{L(t)}\right)^2}} & si \quad \left(\dfrac{P}{L}\right)^2 > 0{,}1 \\ ETR = P & \text{sinon} \end{cases}$$

with

$$L(t) = 300 + 25.t + 0.05.t3$$

ETR: annual real evapotranspiration (mm);

t: mean annual temperature (°C);

P: annual rainfall (mm).

In this pre-forested area integrated into the N'zi watershed, the runoff coefficient (Cr), varies between 5.21% and 6.77%, according to Youan Ta (2008). Thus, from the mean value, the runoff in each grid cell is estimated according to the annual rainfall of each grid cell (R= Cr.P). It is the average rainfall values over the period 1960 and 2017 that are used. For the calculation of the effective infiltration of each grid box, the following is therefore deduced: Ie = P- (ETR + R). Furthermore, for the combination of criteria to develop an indicator, the choice of class is inspired by previous work by the Inter-African Committee for Hydraulic Studies (Jourda and al., 2006). Thus, five class are defined: "very weak", "weak", "medium", "strong" and "very strong". As the criteria are measured on different scales, a codification of these is necessary for a good multi-criteria analysis. Thus, a common interval of 1 to 10 was chosen for this operation, taking into account previous studies carried out by Saley (2003), Jourda and al, (2006), Abdoubabaye, (2012), Assemian and al (2014) and Fulvie and al, (2012). A score of 10 is assigned to the "very strong" class contributing to the excellent achievement of the indicator under consideration. In the opposite case, a grade of 1 is attributed to this class. For the weighting of the criteria, the method developed by Saaty (1977) was applied. Unlike the technique based on the arbitrary choice of weights, this one uses mathematical calculations that generate weighting coefficients (weights) whose sum is equal to 1. For the production of thematic maps, the full aggregation method was applied. It allows all the criteria for each indicator to be integrated and their weighted values to be summed (Joerin, 1995; Saley, 2003; Martin and al, 2004; Jourda and al, 2006; Youan Ta and al, 2015). This approach is summarized by the following equation:

$$I = \sum_{i=1}^{n} WiXi$$

with

I: the result or index of the indicator

Wi: the weight of the criterion

Xi: the standardized value of the criterion of factor i.

Thus, the classifications, codifications and weightings of the indicator criteria: Accessibility, Exploitability and Groundwater Potential are illustrated in Tables 2, 3 and 4. The ARCGIS 10.2 software is a tool with complete functionalities to perform this multi-criteria analysis thanks to its "Raster Calculator" functions in the "Spatial Analyst Tool" menu. Thus, at the end of the process, the four thematic class retained after aggregation are: bad, mediocre, good and excellent.

Table 2: Classification and coding of criteria for the Accessibility Indicator

	Criteria	Criteria Qualifiers	Class	Coding
Indicator	Probability of success (%) (weight: 0,25)	Very weak	< 30 %	1
		weak	30 à 45 %	3
		Medium	45 à 60 %	5
		Strong	60 à 75%	8
		Very strong	>75%	10
Accessibility	Depth of the work (m) (weight: 0,75)	Very weak	< 35 m	10
		weak	35 à 45 m	8
		Medium	45 à 55 m	5
		Strong	55 à 70 m	3
		Very strong	> 70 m	1

Table 3: **Classification and coding of operability indicator criteria**

	Criteria	Criteria Qualifiers	Class	Coding
Indicator	Exploitation Flow (m^3/h) (weight: 0,75)	Very weak	< 1,5 m^3/h	1
		weak	1,5 à 2,5 m^3/h	3
		Medium	2,5 à 5 m^3/h	5
		Strong	5 à 10 m^3/h	8
		Very strong	> 10 m^3/h	10
Exploitability	Static level (m) (weight: 0,25)	Very weak	< 6 m	10
		weak	6 à 16 m	8
		Medium	16 à 26 m	5
		Strong	26 à 36 m	3
		Very strong	> 36 m	1

Table 4: Classification and coding of criteria for the indicator Groundwater potential

	Criteria	Criteria Qualifiers	Class	Coding
Indicator	**slope** (%) (weight : 0, 128)	Very weak	< 0,1	10
		weak	0,1 à 1,5	8
		Medium	1,5 à 2,5	5
		Strong	2,5 à 3,5	3
		Very strong	>3,5	1
	Effective infiltration (mm) (weight: 0, 331)	Very weak	< 60	1
		weak	60 à 80	3
		Medium	80 à 100	5
		Strong	100 à 120	8
		Very strong	> 120	10
GROUNDWATER POTENTIAL	**Drainage density** (km/km^2) (weight : 0,049)	Very weak	< 0,50	10
		Weak	0,50 à 1,0	8
		Medium	1,0 à 1,5	5
		Strong	1,5 à 2,0	3
		Very strong	> 2,0	1
	Fracturing density (km/km^2) (weight : 0,196)	Very weak	< 1,0	1
		weak	1,0 à 1,5	3
		Medium	1,5 à 2,0	5
		Strong	2,0 à 2,5	8
		Very strong	> 2,5	10
	Induced permeability ($x10^{-5}m/s$) (poids : 0,209)	Very weak	< 1,0	1
		Weak	1,0 à 1,5	3
		Medium	1,5 à 3,0	5
		Strong	3,0 à 5,0	8
		Very strong	> 5,0	10
	Alteration thickness (m) (weight : 0,086)	Very weak	< 5,0	1
		weak	5,0 à 15	3
		Medium	15 à 25	5
		Strong	25 à 40	8
		Very strong	> 40	10

Moreover, in a fissured environment, the groundwater resource sought must be easily accessible, exploitable and of good potential (Jourda, 2006; Jouan Ta, 2008; Youan Ta and al, 2015; Assemian, 2014). Thus, the indicators Accessibility, Exploitability and Groundwater Potentiality are used to determine the sites favourable to drilling sites for high flow rates (Youan Ta, 2008; Assemian, 2014; Assemian and al, 2014 and Youan Ta and al, 2015). A combination of these three indicators was defined following a comprehensive aggregation approach (Youan Ta, 2008; Assemian, 2014; Youan Ta and al, 2015). Table 5 presents the codes assigned to the thematic class for each indicator taken here as criteria. This method creates new class, that are represented by numbers in which the participation of each criterion can be easily determined. For example, the code "432" is derived from a combination of the following criteria:

- ‘’excellent" groundwater potential (400);
- ‘’good" exploitability (30);
- ‘’poor" accessibility (2);
- Thus: 432 = 400+30+2".

The combination of these criteria by the codification technique gives different thematic class, resulting in 64 class (Table 6). But by aggregation, four main class are defined for the mapping of zones favourable to the establishment of boreholes for good flow rates. Thus, for example, a very favourable zone for the implantation of drilling (excellent) can be at the same time: excellent potentiality (400), excellent exploitability (40) and excellent accessibility (4), has a code of 444. But, a zone that is not at all favourable (bad) may be an area with bad potentiality (100), bad exploitability (10) and bad accessibility (1), has a code of 111. Thus, by the same procedure, in Table 6, the different colors of the codes present the four thematic class: bad, mediocre, good and excellent zones favourable for drilling to obtain high flow rates.

Table 5: Class and Codes of Criteria (Potentiality, Exploitability and Accessibility)

	Criteria	Class	Coding
Indicator	**Water potential underground**	Excellent	400
		Good	300
		Mediocre	200
		Bad	100
Zones favourable to the implementation of good drilling rates	**Exploitability**	Excellent	40
		Good	30
		Mediocre	20
		Bad	10
	Accessibility	Excellent	4
		Good	3
		Mediocre	2
		Bad	1

Table 6: Aggregation of criteria by coding

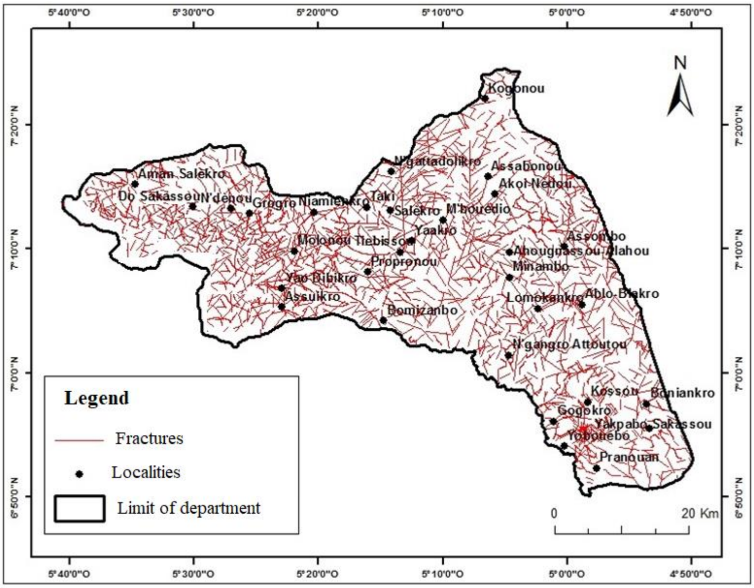
Criteria1: Water potential underground	Criteria 2: Exploitability — Bad	Mediocre	Good	Excellent	Criteria 3: Accessibility
Excellent	414 ; 413 ; 412 ; 411	424 ; 423 ; 422 ; 421	434 ; 433 ; 432 ; 431	444 ; 443 ; 442 ; 441	Excellent Good Mediocre Bad
Good	314 ; 313 ; 312 ; 311 ;	324 ; 323 ; 322 ; 321	334 ; 333 ; 332 ; 331	344 ; 343 ; 342 ; 341	Excellent Good Mediocre Bad
Mediocre	214 ; 213 ; 212 ; 211	224 ; 223 ; 222 ; 221	234 ; 233 ; 232 ; 231	244 ; 243 ; 242 ; 241	Excellent Good Mediocre Bad
Bad	114 ; 113 ; 112 ; 111	124 ; 123 ; 122 ; 121	134 ; 133 ; 132 ; 131	144 ; 143 ; 142 ; 141	Excellent Good Mediocre Bad

According to Youan Ta and al, (2015), these classes are either: unsuitable (normal character); acceptable for village hydraulics; acceptable for improved village hydraulics; and suitable for urban water supply. Within the GIS that was set up, all combinations were made in Raster mode using the "Raster Calculator" tool in the "Spatial Analyst Tool" menu of ARCGIS10.2. This "raster calculator" tool can be used to elaborate all possible queries through the combinations that it allows to perform.

RESULTS

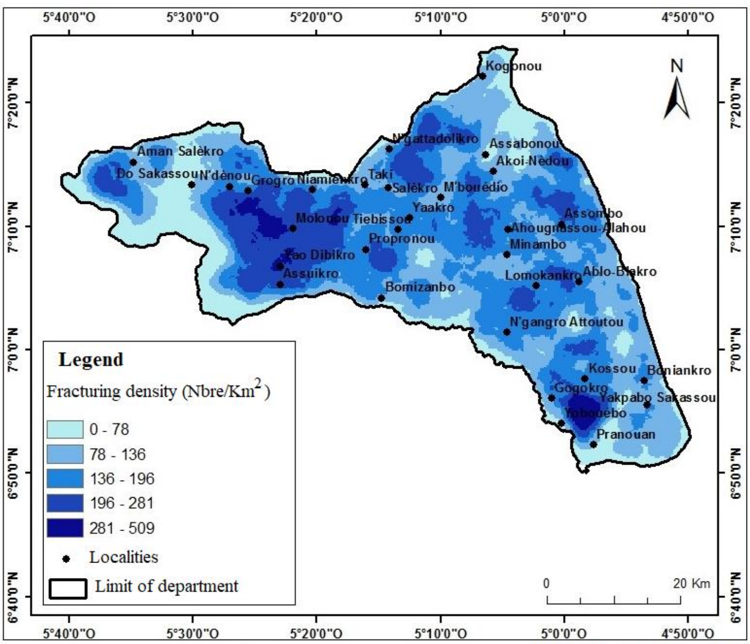
Hydraulic properties of fractures

The extraction of fractures on the DTM band of the processed ASTER sensor was able to reveal 1347 hectometric and kilometric fractures (figure 4). The fracture lengths vary between 0.24 km and 11.25 km, with a mean of 2.31 km and a standard deviation of 1.28 km. The sum of these fracture lengths amounts to 3117.5 km. These fractures are distributed over the entire territory of the department. The fracture density map established on ARCGIS10.2, using the fracture network, made it possible to see the concentration of these fractures at the scale of the department (Figure 5). Zones with high fracturing densities are more productive in groundwater. These are concentrated in the west, north and south. The high density is more concentrated in schistose environments than in granite environments. Indeed, in the sub-prefectures of Molonou in the central-western part and Yapkobo-sakassou in the south-eastern part of the schists, the fracture density is higher. While in the center, on granitic rocks, the density is medium. To highlight the relationship between fracturing and drilling productivity, we cross-referenced the fracturing network data with the drilling data. Indeed, the positioning of the drill holes on the fracture network in the same coordinate system (UTM, WGS, 84, zone 30N) allowed us to see the influence of these accidents on the exploited flows (figure 6). The analysis of this overlay shows that, on the whole, not all the drill holes intercept the fractures. Most of the boreholes located near kilometric fractures have average (2.5 m^3/h to 5 m^3/h) and high (>5 m^3/h) flow rates. Zones with high fracturing densities have high flow rates due to the strong interconnection between the fractures.



Source: www.earthexplorer.usgs.gouv/ Realization : SAMAKE Y., 2018

Figure 4: Detailed fracturing map of the Tiébissou department



Source: www.earthexplorer.usgs.gouv/ Realization : SAMAKE Y., 2018

Figure 5: Fracturing density map of the Tiébissou department

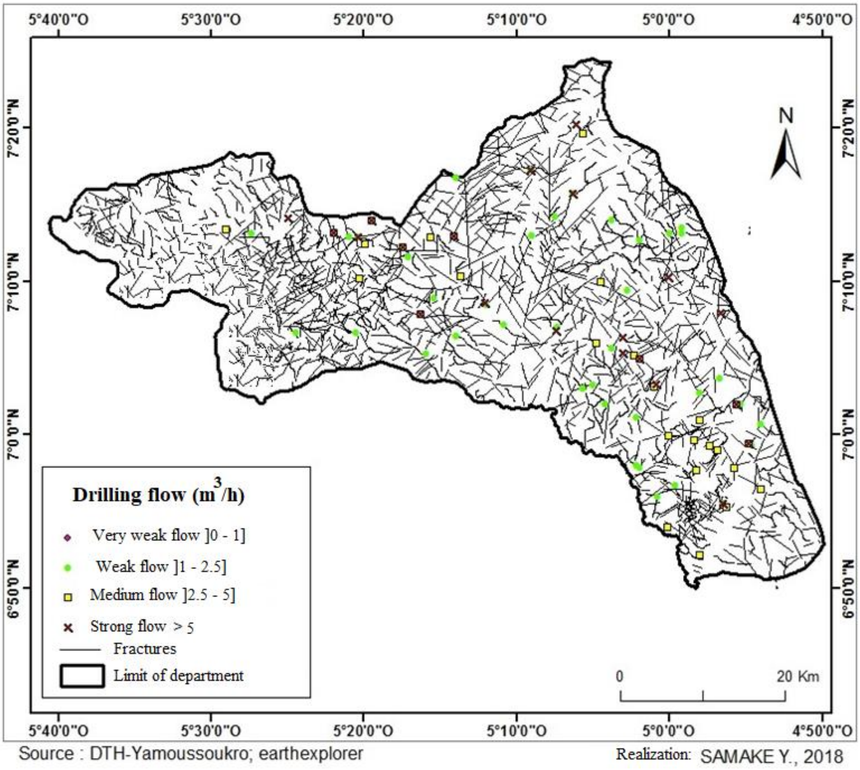


Figure 6: Distribution of borehole flow rates as a function of fractures

Mapping of groundwater productive areas

Groundwater is only usable when it is easily accessible by certain factors, the most important of which are the depth of the structures and the probability of success. The study of these two parameters made it possible to produce the accessibility map of the groundwater resources of the Tiébissou department (Figure 7). This map is characterized by four (4) thematic class of unequal distribution. The class of poor accessibility occupies 18% of the surface area, has 442.95 km². This area is characterized by very large depths, with low probabilities of success. The bad accessibility class covers an area of 884.95 km², or 37% of the total area. The good accessibility class occupies 34% of the department, or 819.4 km². It is characterized by low drilling depths and a good probability of success. The excellent accessibility class occupies only 11% of the area, so 262.7 km² (Figure 8). The areas of good and excellent groundwater accessibility are found in the south, center and west. Some medium and high flows are found in these areas. The usability of groundwater resources depends on the exploitation flow and the static level. Indeed, the combination of these two criteria has made it possible to draw up the map of groundwater exploitability of the Tiébissou department (figure 9) with a great importance given to the exploitation flow rate. On this Exploitability map, four class can be identified. The class of bad exploitability covers an area of 530.2 km², so 22% of the total area of the department. It is characterized by areas with very low exploitation flows and very high static levels. The class with bad exploitability is distributed over the whole department. It covers an area of 574.7 km², so 24% of the total area. The class of good Exploitability is characterized by sectors with medium and high flow rates, and with a relatively low static level. This class is the most representative of the study sector with an estimated occupation proportion of 39%, so 931.8 km² of the total area. The class with excellent Exploitability covers only 16% of the department, with an area of 373.8 km² (Figure 10). From this analysis, it appears that the Exploitability in groundwater at the scale of the department of Tiébissou is relatively average with a proportion of 54%.

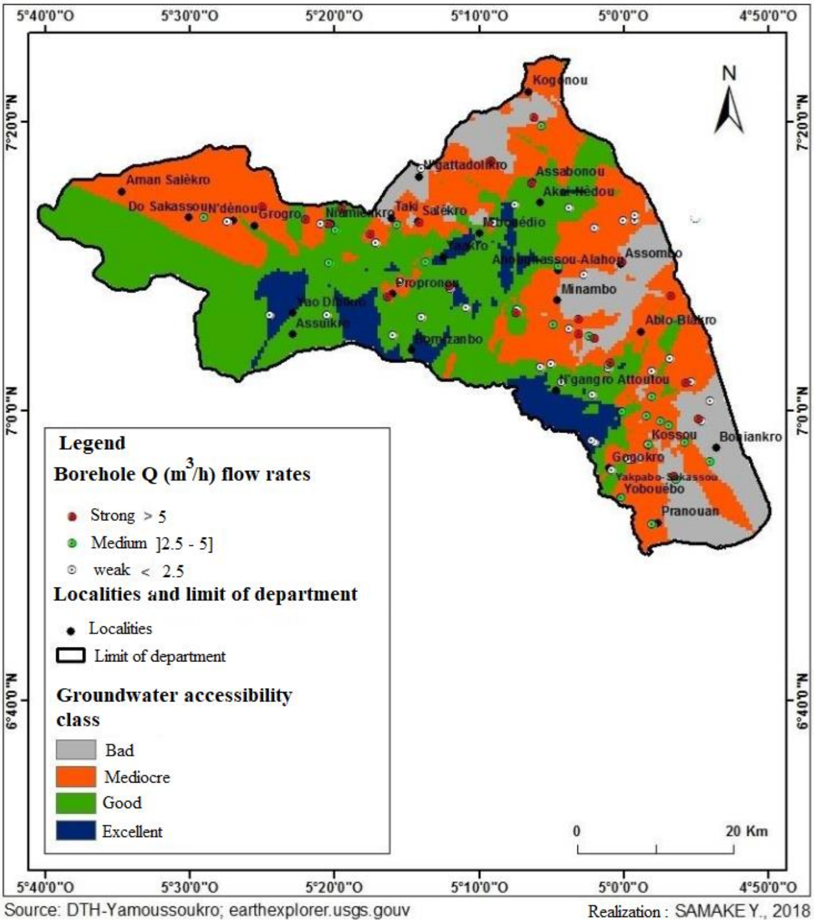


Figure 7: Groundwater Accessibility Map of the Tiebissou Department

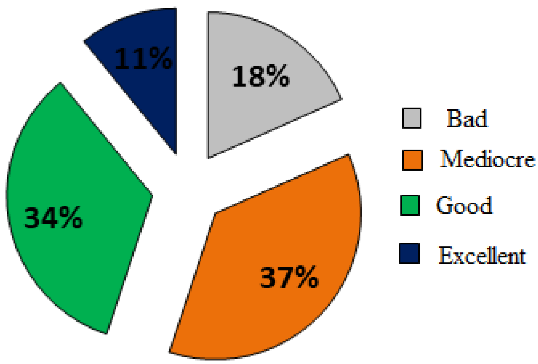


Figure 8: Distribution of accessibility class

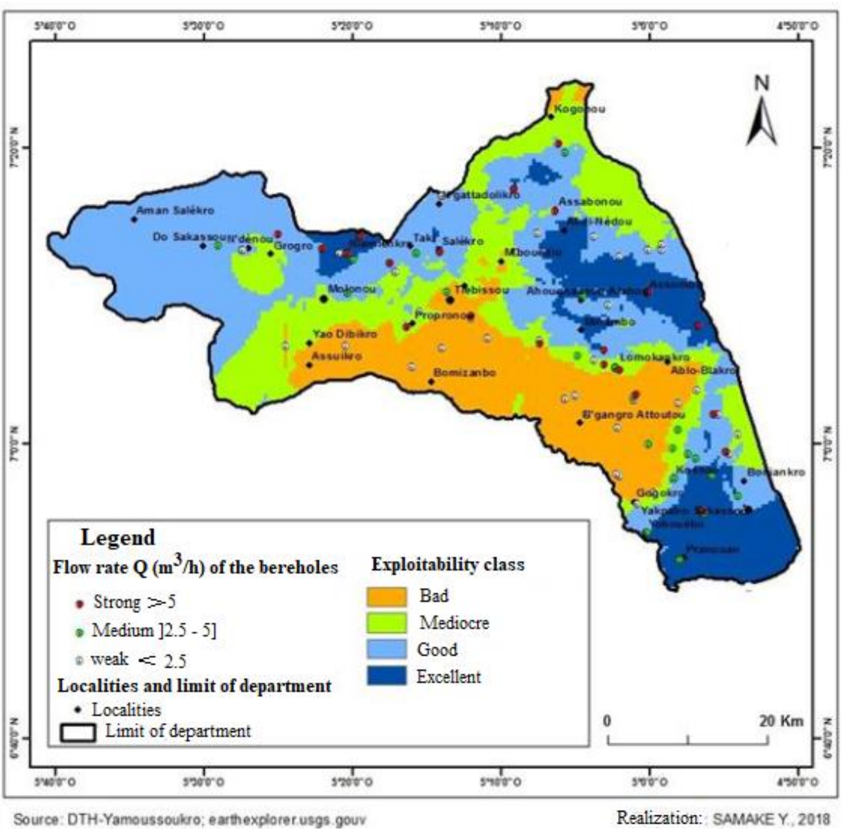


Figure 9: Groundwater Exploitability Map of the Tiebissou Department

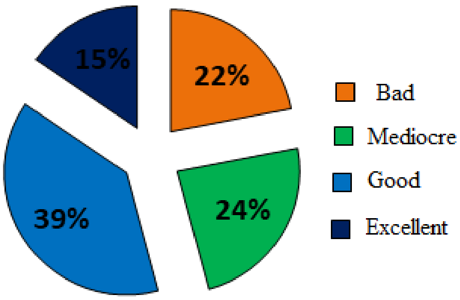


Figure 10: Distribution of Exploitability Class

The groundwater potential map is illustrated in Figure 11. Four class are also derived from this mapping. Areas with bad potentiality occupy only 383.2 km², or 16% of the total area. These zones are relatively less fractured. Recharge, induced permeability and alteration are low. This explains their low groundwater potential. Zones with poor potentiality occupy 33% of the department, with an area of 789.28 km². The mediocrity of these zones can be explained by their low induced permeabilities because the basement is submerged in them. The zones with good potential cover a total area of 877.24 km², or 36% of the total area of the department (Figure 12). These zones are characterized by relatively low slopes, which indicates a good supply of groundwater. Fracturing is intense and contributes to the recharge of the water tables. The thicknesses of alteration vary between 45 and 60 m. All in all, these zones combine factors that favour the accumulation of water and are therefore very productive in terms of groundwater. Finally, the areas with excellent potential cover only 360.3 km², so 15% of the total surface area. The increased productivity of these zones is justified by the very high number of fractures. The fractured zones show areas of very high permeability favouring the infiltration and drainage of groundwater. The majority of the holes drilled in the good and excellent potential zones have average (2.5 to 5 m^3/h) and high (>5m^3/h) flow rates (Figure 11).

Moreover, the combination of the three indicators of accessibility, exploitability and groundwater potential has made it possible to produce a map of the zones favourable to the implantation of drilling for good flow rates (Figure 13). The bad (unfavourable) zones occupy only 12% of the surface area, with approximately 292.33 km². In these areas, groundwater is difficult to access and unusable. The aquifer is less productive of groundwater. Boreholes drilled in these sectors will certainly offer low flow rates. The scarcity of fractures explains this result. As a consequence, poor hydraulic conductivity and low transmissivities are observed in these sectors. The zones that are poorly suited for drilling occupy 62% of the area, or 1493.48 km^2. Here, the groundwater is more or less accessible and hardly exploitable. The region is also not very productive in terms of groundwater. These areas constitute resources that are more or less suitable for supplying rural areas (village hydraulics) where the demand for water is more modest compared to urban areas. The areas that are simply favorable to the installation of boreholes to obtain good flow rates occupy a proportion of 25%, so an area of 609.25 km^2 (Figure 14). In these areas, groundwater is easily accessible and exploitable. Their groundwater potential is good. Boreholes drilled in these areas can certainly provide significant flows. They can be used for drinking water supply in urban areas where the population is large. The areas that are excellently suited for drilling represent only 1% of the department with an estimated surface area of 14.94 km². These zones coincide with the areas of highest fracture density in the department. These two categories of zones are influenced by the interconnection of fractures and the intrusion of the thin layer of greenstone alteration allowing good underground hydraulic conductivity and good aquifer recharge. Let us deduce that these zones are capable of providing higher flows to cover the increasing water needs (urban hydraulics) because of their high hydraulic potential. On the whole, sites suitable for the implementation of drilling at good flow rates are included in areas with high fracturing density and high alteration thicknesses. The more densely fractured the environment, the more productive the groundwater. The high thickness of alteration also favours the accumulation of groundwater for the recharge of the underlying fissured horizon.

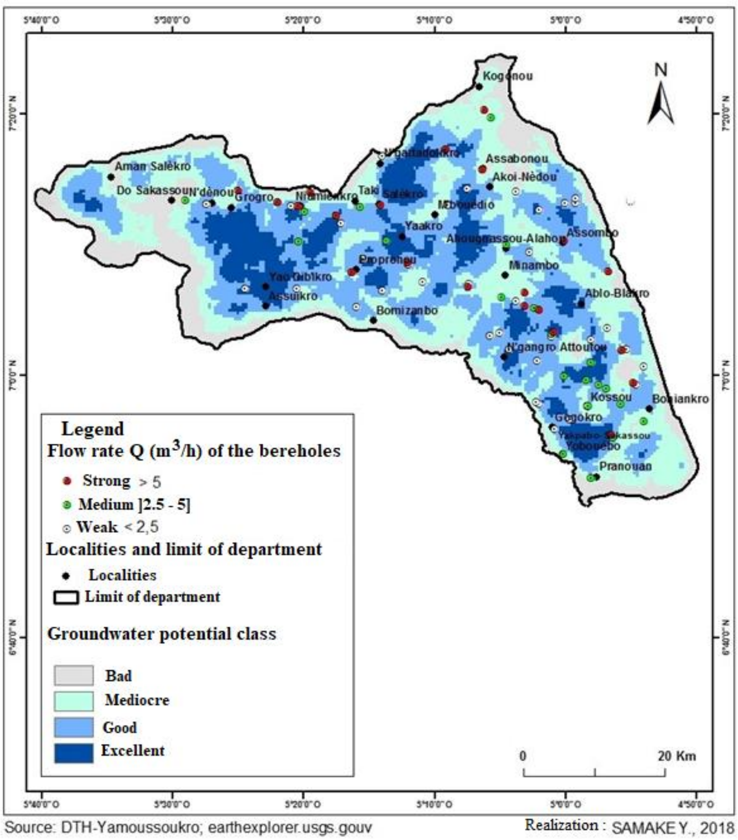


Figure 11: Groundwater Potential Map of the Tiebissou Department

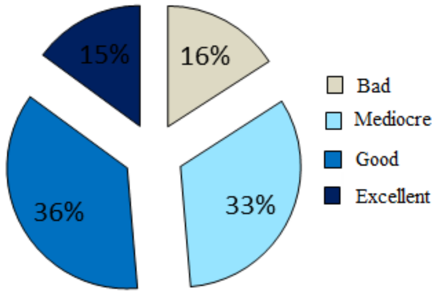
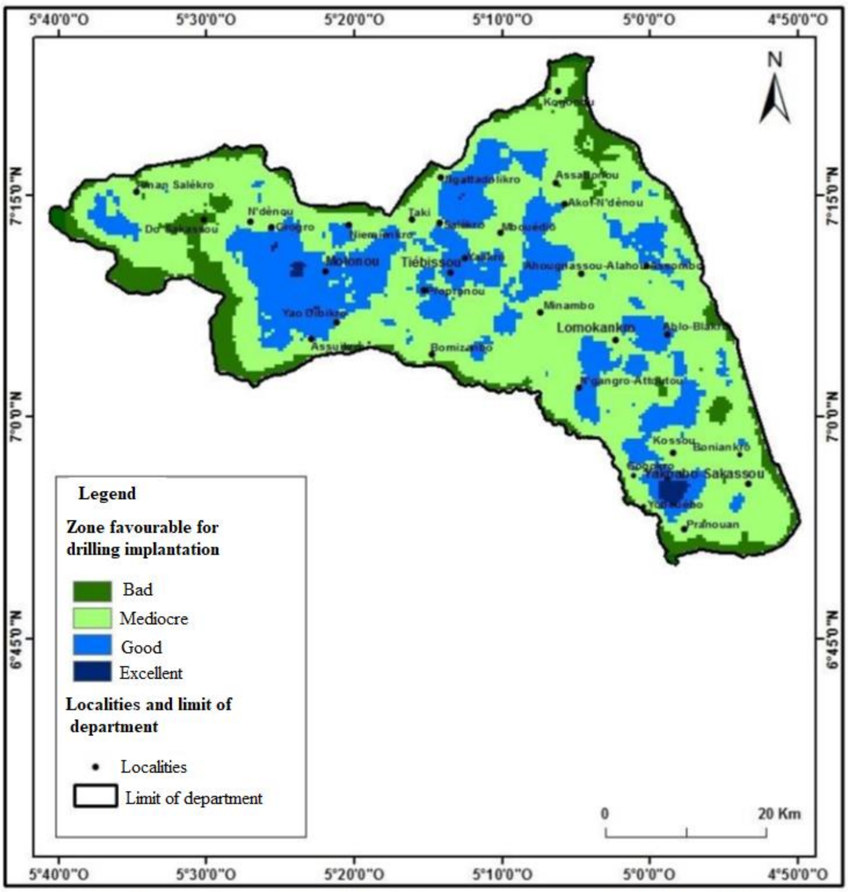


Figure 12: Distribution of potentiality class



Source: DTH-Yamoussoukro; earthexplorer.usgs.gouv   Realization : SAMAKE Y., 2018

Figure 13: Map of zones favourable to the implementation of good flow drilling

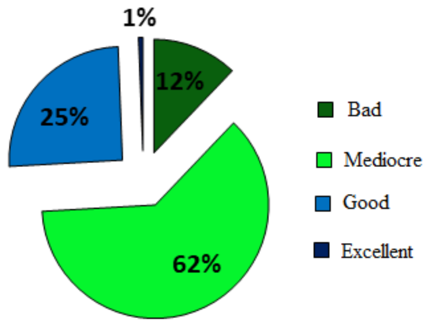


Figure 14: Distribution of zones favourable for drilling

DISCUSSION

Since the study area is entirely forested, the use of optical imagery for precise fracture mapping would not be an easy task. Indeed, the reflectance of dense vegetation in certain wavelengths of the visible and infrared very often masks morphostructures indicative of fractures or faults (Assemian and al, 2018). These morphostructures are marked accidents in the topography and may reveal an alternation of rocks of different hardness or the presence of faults or tectonic fractures (Scanvic, 1983; Derion and al, 1995 ; Koudou and al, 2014). A regional fracture in forested areas is often marked by a fairly narrow valley incision due to the preferential erosion to which it is subject. The observation of a structural lineament in relief leads rather to interpret this anomaly as ruptures or surface roughness (Derion and al., 1995). DTM (Digital Terrain Model) images that describe the morphology of the landscape, the model or more simply the relief, such as radar images, can be exploited to conduct a study of structural accidents indicative of faults and open or closed fractures. Thus, in this study, the processing of the DTM band of the ASTER sensor allowed to enhance the structural accidents indicative of faults and fractures. Thus, the network of fractures confronted with the fractures coming from the photo-geological maps shows identities and similarities in the different regions of the study area; this allowed us to validate the fracture map coming from the DTM band. In addition, this map shows more detailed fractures than those from the photo-geological maps, which allowed us to produce a more detailed fracture density map. This is why the zones where the fracturing density is high, the drilling flows in these areas are important. The application of GIS in a multi-criteria analysis is a method commonly used by researchers to study groundwater productivity in basement aquifers (Biemi. and al. 1995; Savané and al. 1995; El Hadani. 1997; Haouchine and al. 2011; Fulvie and al. 2013 and Assemian, 2014, Jourda and al., 2006). Through the compilation of several criteria in a GIS environment, revealing maps of large basement groundwater reservoirs can be produced. Here, the groundwater potentiality map shows us the highly productive zones, capable of providing significant drilling flows. Thus, when associated with the accessibility and exploitability indicators, we obtain a map of the zones favourable to the implantation of drilling for good flow (Jourda and al 2006; Assemian and al, 2014 and Youan Ta and al, 2015). This means that it will be possible to have very high flow rates for drilling at modest depths. These areas reduce the cost of drilling and will provide very high flows. Remote sensing methods and hydrogeological information systems, as well as geophysics, can easily contribute to hydrogeological prospecting work.

CONCLUSIONS

The processing of the ASTER sensor DTM strip has allowed to map the fracture network of the Tiebissou department. A total of 1347 kilometric and hectometric fractures were extracted. The fracture lengths vary between 0.24 km and 11.25 km. The fracture density shows a high variability. The zones with very high density have a sufficiently well connected fracture network, which favours good water infiltration and transmissivity. These areas are therefore very productive in terms of groundwater. Drilling near kilometric fractures and in zones with high fracture densities has significant flow rates. The GIS methods (multi-criteria analysis) applied show that 45% of the basement of the Tiébissou department has good and excellent groundwater accessibility and 54% has good and excellent exploitability. In addition, 51% of the territory has a good and excellent groundwater potential. Zones that are very favourable for the implementation of drilling to obtain good flow occupy a proportion of 26%, representing a surface area of 624.19 km^2. These are scattered almost everywhere and are more concentrated in the west. In these areas, groundwater is easily accessible and exploitable. They are also very productive groundwater sectors.

REFERENCES

ABOUBAYE M.S. (2012). Evaluation des ressources en eau souterraine dans le bassin de Dargol (Liptato-Niger), Thèse de Doctorat Université de Liège, Belgique, 265p.

ASSEMIAN A.E. (2014). Etude des potentialités en eau souterraine du département de Bongouanou, centre-est de la Côte d'Ivoire par télédétection et SIG. Thèse unique de doctorat, université Félix Houphouët Boigny, 258 p.

ASSEMIAN A.E, KOUAME K.F, DJAGOUA E.V., AFFIAN K, JOURDA P.R., ADJA A, LASM T, BIEMI J. (2013). Etude de l'impact des variabilités climatiques sur les ressources hydriques d'un milieu tropical humide : cas du département de Bongouanou (Est de la Côte d'Ivoire). Revue des sciences de l'eau, ISSN 1718-8598. Vol 26, No 3, pp. 247-261.

ASSEMIAN A.E, KOUAME D.A, MOBIO A.B.H., KOUAME A.N., KOUDOU A. KOUADIO H.B, N'da D.H. THERRIEN R, RAZACK M. (2014). Application de la télédétection et les méthodes d'analyse multicritère à l'étude de la variabilité spatiale des potentialités en eau souterraine d'un aquifère de socle d'une région tropicale humide de l'Afrique de l'ouest : cas du département de Bongouanou, est de la Côte d'Ivoire Revue photo-interprétation european journal of applied remote sensing, No 2014/3-4. pp.120-134.

ASSEMIAN E.A. ADJA M.G, KOUDOU A, THERRIEN R, RAZACK M. (2018). Télédétection radar, analyse statistique et multicritère appliquées à l'étude de la productivité en eau souterraine et de la vulnérabilité à la pollution des aquifères fissurés du département de Bongouanou, Côte d'Ivoire. Revue photo-interprétation european journal of applied remote sensing No 4, Vol. 51, pp.16-48.

ASSEMIAN A.E, KANGA K.M.H, KOUASSI K, YAO K.J.J, KOFFI B.E, (2018). Analyse des variations de la recharge des eaux souterraines du socle de Dimbokro, zone tropicale humide du centre-est de la Côte d'Ivoire, face au changement climatique. Revue ivoirienne des sciences et technologies ISSN : 1813-3290, N°31 (2018), p 84-107.

BIEMI J. (1992). Contribution à l'étude géologique, hydrogéologique par télédétection de bassins versants subsahéliens du socle précambrien d'Afrique de l'ouest, hydrostructure, hydrodynamique, hydrochimie et isotopie des aquifères discontinus de sillon et aire grantique de la haute Marahoué (Côte d'Ivoire). Thèse de doctorat sciences naturelles. Université Abidjan, 479p.

BIEMI J, JOURDA P.J, GWYNS H. (1995). Positionnement, productivité et gestion des forages en milieu fissuré de Côte d'Ivoire par Télédétection et Système d'Information Géographique, in Atelier International, Télédétection et gestion des ressources en eau, Montpellier, pp. 138-162.

COULIBALY T.J H. (2009). Répartition spatiale, gestion et exploitation des eaux souterraines : cas du département du Katiola, région des savanes de Côte d'Ivoire, Thèse de doctorat, Université Paris Est, France, 142p.

COOPER H.H et JACOP C.C. (1946). A generalized graphiquical method for evaluating formation constants and sommarizing well field history, Transactions of the American. Geophysical Union, Vol.. 27, pp. 526-534.

DERION I.P DELOR C.I, SIMEON Y et YAO B. (1995). Contribution of remote sensing and other techniques to the geodynamic setting of the paleoproterozoic in Ivory Coast (west Africa): comparison to fied data. Géodynamique du paléoprotérozoique, Orléans 17 novembre 1995, séance spécialisée de la société géologique de France, résumé.

DEWANDEL B, LACHASSAGNE P, ZAIDI F.K et CHANDRAC S. (2011). A conceptual hydrodynamic model of a geological discontinuity in hard rock aquifers : Exemple of a quartz reef in granitic terrain in South India. BRGM. Water Division, Ressource Assessment, Discontinous Aquifers Journal of Hydrology, No 405, pp.474-487.

DJE BI D. S. (2017). Géomorphologie et positionnement des forages dans le département de Tiébissou., Mémoire de Master, Université Alassane Ouattara, Bouaké, 99p.

EL HANDANI D. (1997). « Télédétection et système d'information géographique pour la gestion et la recherche de l'eau. » in: Remole Sensing and Geographic lnformalion Systems for Design and Operation of Water Resources Systems, IAHS Publication, Maroc, No 242, pp. 197-204.

FRANCISS F.O. (1970). Contribution à l'étude du mouvement de l'eau à travers les roches milieux fissurés. Thèse de Doctorat, université de Grenoble, 108 p.

FULVIE K, SALEY M. B, AKE G. E. et SAVANE I. (2013). Apport de la télédétection et des SIG dans l'identification des ressources en eau souterraine dans la région de Daoukro (Centre-Est de la Côte D'Ivoire). » in : International Journal of Innovation and Applied Studies, ISSN 2028-9324 Vol. 1, No. 1, pp. 35-53

GNAMBA F. M., OGA Y. M. S, GANGNE T., LASM T., BIEMI J, et KOUAKOU Y.K.N. (2014). Analyse de la productivité des aquifères de fissures du sol paléo protérozoïque de la région de Katiola (Centre Nord de la Côte d'Ivoire), European scientific journal, Vol.10, No 5, pp.79-98.

HAOUCHINE A, BOUDOUKHA A, HAOUCHINE F. Z et NEDJAI R. (2011) Cartographie de la recharge potentielle des aquifères en zone aride : cas de la plaine d'El Outaya, Biskra-Algérie. », in : HAL archives-ouvertes, 13p.

JOURDA J.P, SALEY M.B, DJAGOUA E.V, KOUAME K.J, BIEMI J, et RAZACK M. (2006). Utilisation des images Landsat ETM+ pour l'évaluation des potentialités en eaux souterraines dans le milieu fissuré précambrien de la région de Korhogo (Nord de la Côte Ivoire) : approche par analyse multicritère et test de validation. Revue de télédétection, Vol.5, No 4, pp.339-357.

JOERIN F., (1995). Méthode multicritère d'aide à la décision et SIG pour la recherche d'un site. Revue internationale de géomatique, Vol.1, No 5, pp. 37-51.

KABRE W. P. (2012). Caractérisation hydrogéologique d'un aquifère en milieu de socle fracturé : Cas De la province du Kourwéogo, Mémoire de master, Institut International d'Ingénierie de l'Eau et de l'Environnement, Burkina Faso, 53p.

KOUASSI A.M., AHOUSSI K.E., YAO K.A, OUREGA W.E.J.A., YAO K.S.B., BIEMI J., (2012.). Analyse de la productivité des aquifères fissurés de la région du N'Zi-Comoé (Centre-Est de la Côte d'Ivoire), Larhyss Journal, No10, pp. 57-74.

KOUDOU A., ASSOMA V.T., ADIAFFI B., YOUAN TA, M., KOUAME, K.F., & LASM T. (2014). Analyses statistique et géostatistique de la fracturation extraite de l'imagerie Asar Envisat du sud-est de la Côte d'Ivoire, Larhyss Journal, No 20, pp. 147-166.

KOUDOU A, SALEY M.B, KOUAME F.K., YOUANT TA M, JOURDA J.P, BIEMI J. (2011). Contribution d'un SIG à la cartographie des secteurs à potentialité aquifère du bassin versant du N'zi au centre de la Côte d'Ivoire. Conférence francophone ERSI, Versailles 5 et 6 octobre 2011. Session Environnement, 26 p. https://sig2011.esrifrance.fr/univ_koudou.aspx

KOUDOU A, GAHI Z.N, ASSEMIAN A.E. (2018). Repercussions of the rainfall dynamic on surface water and groundwater of the n'zi watershed in Côte d'Ivoire. Communication Ref 011. IWFC-2018-RGFC-IAH Hammamet, Tunisia, Mach 19-21.

KOUSSOUBE Y. (2010). Hydrogéologie des séries sédimentaires de la dépression piézométrique de Gondo (Bassin de Sourou) : Burkina Faso/ Mali, Thèse de Doctorat. Université Pierre et Marie Curie, Paris, 265p.

KOUSSOUBE Y. (1996). Hydrogéologie en milieu du socle cristallin du Burkina Faso : cas du bassin versant du bas-fond de Bidi (Province du Yatenga). Thèse université Cheick Anta Diop. Dakar, Sénégal, 238 p.

LAMZOURI H. (2015). Extraction des linéaments géologiques à partir des images Landsat : Cas de la plaine de Tamlit (Haute Atlas Oriental), Mémoire de fin de cycle, Université Sidi Mohamed Ben Abdellah, Maroc, 27p.

LACHASSAGNE P et WYNS R. (2005). Aquifères de socle : nouveaux concepts. Application à la prospection et à la gestion des ressources en eau. Géosciences, 2, 31, p37.

MARTIN J.L HENRY E BOULENIA C MASSON F.X, (2004). Proposition d'outils de gestion et d'aide à la décision dans une moyenne collectivité locale : application à l'exploitation de la ressource en eau souterraine. Acte de la journée d'étude « les territoires de l'eau » Université d'Artois Arras. 74-82.

ROUX J.C., (2005). Aquifère et eau souterraine en France. Ouvrage collecfif tome 1, académie des sciences. BRGM éditions 51 p.

SAATY T.L. (1977). A Scaling method for priorites inhierarchical structures J. Math. Psychology, Vol. 15, pp. 234-281.

SAATY T.L., (1977). A scaling method for priorities in hierarchical structures, Journal of Mathematical Psychology, Vol. 15, pp. 234-281.

SALEY M.B. (2003). Système d'information hydrogéologique à référence spatiale, discontinuité pseudo-image et cartographie thématique des ressources en eau de la région semi-montagneuse de Man (ouest de la Côte d'Ivoire). Thèse unique de doctorat, université de Cocody, 211 p

SAVANE I et BIEMI J. (2000). Cartographie des aquifères de fissures en milieu cristallin du nord-ouest de la Cote d'Ivoire par télédétection. La télédétection francophonie : analyse critique et perspectives. Ed AUF, pp. 279-288.

SAVADOGO A.N. (1984) Géologie et hydrogéologie du socle cristallin de haute Volta : étude régionale du bassin versant de la Sissili. Thèse Sciences naturelles. Université Grenoble, 350p.

SAVANE I. (1997). Contribution à l'étude géologique et hydrogéologique des aquifères discontinus du socle cristallin d'Otienné (Nord-ouest de la Côte d'Ivoire). Apport de la télédétection et d'un système d'information hydrogéologique à référence spatiale. Thèse d'état, université de Cocody, 396p.

SAVANE I, GOZE B.B et GWYNS H, (1995). Evaluation des ressources en eau dans le socle par l'étude des fractures à l'aide des données Landsat (Bassin d'Odiénné, Côte d'Ivoire), in : Atelier International, Télédétection et gestion des ressources en eau, Montpellier, pp. 89-101.

SCANVIC J.Y., (1983). Télédétection aérospatiale et informations géologiques. Editions du BRGM, Manuels et Méthodes, Vol. 24, 284 p.

SORO G, SORO N, AHOUSSI K E, LASM T, KOUAME F. K, SORO T. D et BIEMI J. (2010). Evolution des propriétés hydrauliques des aquifères fracturés des formations cristalline et métamorphique dans la région des Lacs (centre de la Côte d'Ivoire) » in : Estudios geologicos, Vol. 66, No 2, ISSN : 0367-0449, Université de Cocody, Abidjan, pp. 227-242.

YOUAN TA M. (2008). Combinaison de la télédétection et des systèmes d'informations géographiques à la prospection hydrogéologiques du socle précambrien d'Afrique de l'ouest : cas de la région de Bondoukou Nord-Est de la Côte d'Ivoire. Thèse unique de doctorat, université de Cocody, Abidjan, 236 p.

YOUAN TA M., YAO K.A.F., BAKA D., DE LASM Z. O., LASM T., ADJA M.G., KOUAKOU S., ONETIE Z.O., JOURDA J.P.R., BIEMI J. (2015). Cartographie des zones potentielles à l'implantation des forages à gros débit en milieu fissuré par analyse multicritère cas du département d'Oumé (Centre – Ouest de la Côte d'Ivoire), Larhyss Journal, ISSN 1112-3680, No 23, pp. 155-181.